An Overview of the Hydrogen Storage Materials

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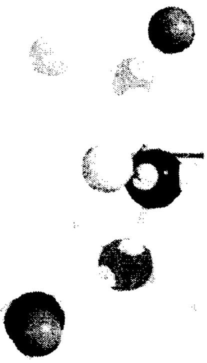
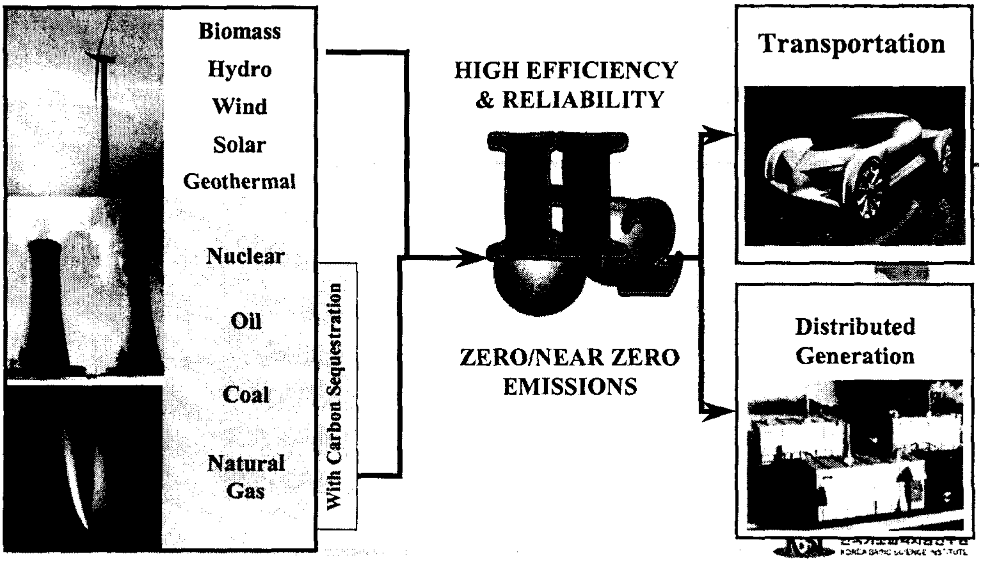


Hae Jin Kim

Frontier Research Laboratory

KBSI

Why Hydrogen? It's abundant, clean, efficient, and can be derived from diverse domestic resources.



Biomass
Hydro
Wind
Solar
Geothermal

Nuclear

Oil

Coal

Natural Gas

With Carbon Sequestration

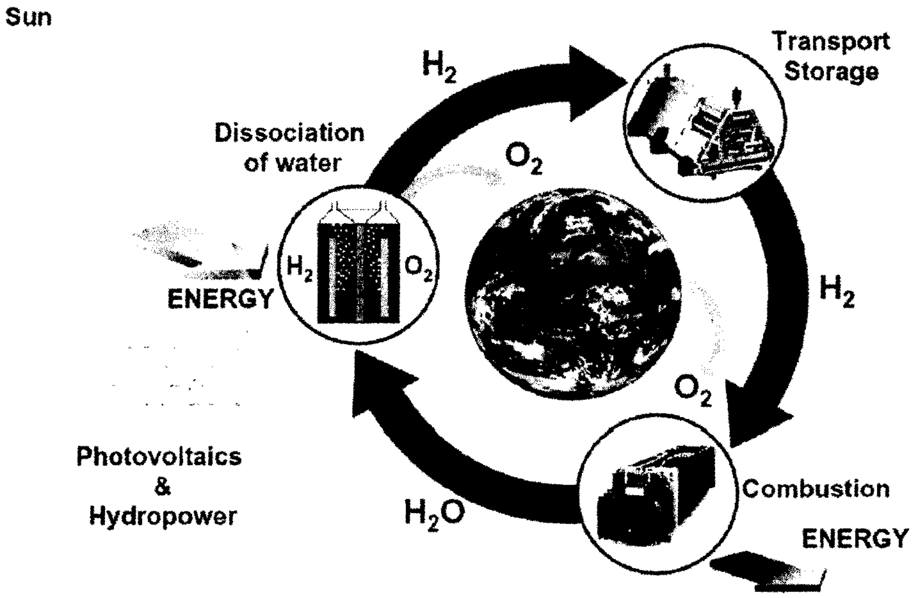
HIGH EFFICIENCY & RELIABILITY

ZERO/NEAR ZERO EMISSIONS

Transportation

Distributed Generation

HYDROGEN CYCLE



Sun

Dissociation of water

H_2

Transport Storage

O_2

ENERGY

H_2 O_2

H_2

O_2

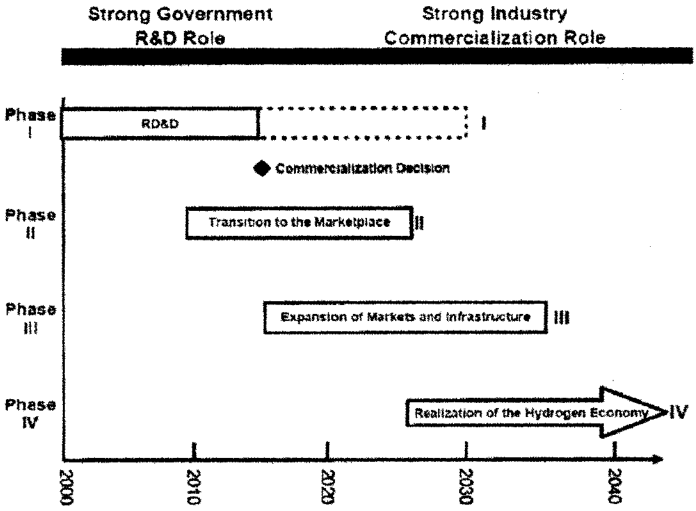
Photovoltaics & Hydropower

H_2O

Combustion

ENERGY

Time for Hydrogen Economy



Strong Government R&D Role

Strong Industry Commercialization Role

Phase I — RD&D — I

◆ Commercialization Decision

Phase II — Transition to the Marketplace — II

Phase III — Expansion of Markets and Infrastructure — III

Phase IV — Realization of the Hydrogen Economy — IV

Transitional Phases

- I. Technology Development Phase
- II. Initial Market Penetration Phase
- III. Infrastructure Investment Phase
- IV. Fully Developed Market and Infrastructure Phase

DOE Hydrogen Storage R&D Program Approaches

Chemical Storage (2004)
- *$NaBH_4$ Process Chemistry*
- *Life-Cycle Analyses*
- *Other Hydrides*

Complex Metal Hydrides
- *$NaAlH_4$ System Integration*
- *Hydride Materials R&D*
- *Kinetics/Mechanistic Studies*

Standard Testing Procedures/Facilities

Advanced Concepts (2004)
- *TBD*

Carbon
- *Kinetics/Mechanistic Studies*
- *Process R&D*
- *Structure/Property Analyses*

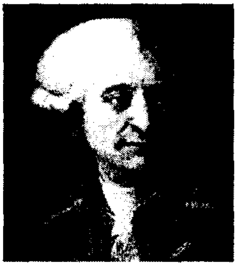
Compressed/Liquid Tanks
- *5,000/10,000 psi Tanks*
- *Semi-Conformal System*
- *Tank Liners/Overwrap Materials*
- *Insulated Pressure Vessels*
- *Unusual Shapes*

From Patrovic & Milliken (2003)

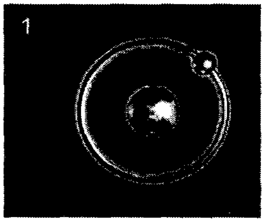
History

- **Discovered about 200 years ago (1766)**

Henry Cavendish (1731-1810)



Antoine Lavoisier (1743-1794)



History

- In 1931, hydrogen was discovered to have isotopes

Harold C. Urey (1893-1981)
Nobel Laureate 1934

vs.

Frederick Soddy (1877-1956)
Nobel Laureate 1921

Isotopes of Hydrogen

- Three common isotopes:
  - Protium (H)
    - common hydrogen
    - 99.985% abundant
  - Deuterium (D)
    - one neutron
    - 0.015% abundant
  - Tritium (T)
    - two neutrons
    - 1x10^{-15}% abundant

$^{1}_{1}H$	$^{2}_{1}H$	$^{3}_{1}H$
Protium	Deuterium	Tritium
1 Proton	1 Proton	1 Proton
0 Neutron	1 Neutron	2 Neutrons
Henry Cavendish (1776)	Harold C. Urey (1931)	Ernest Rutherford (1934)
		Unstable with a half-life of 12.43 years

H/D=6000

Two groups of H molecule

I = 0, antiparallel nuclear spin

Para

I = 1, parallel nuclear spin

Ortho

- Normal Hydrogen is 75% Ortho, 25% Para (at 298 K)
- The melting and boiling points of para hydrogen are ca. 0.1 K lower than those of normal hydrogen.
- At T=0 K, ALL the molecules must be in a rotational ground state (in the para form)
- The ortho form cannot be prepared in the pure state

Mass energy densities for various fuels

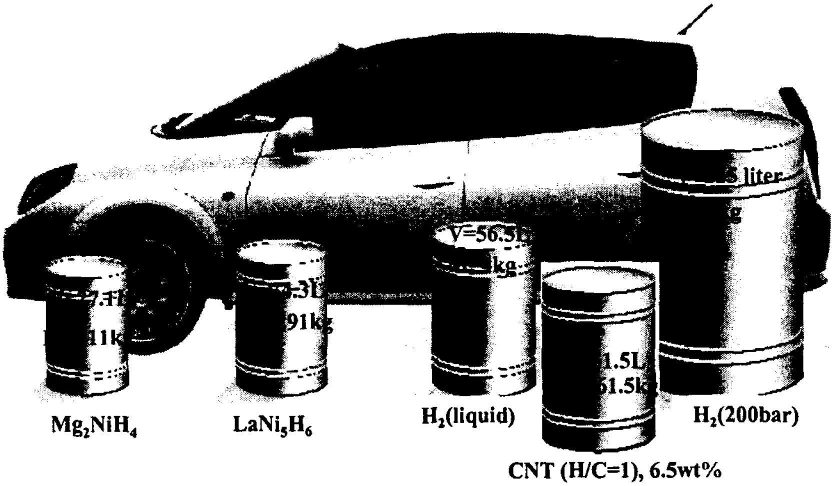
Increasing molecular wt.

Fuel	Hydrogen weight fraction	Ambient state	Mass energy density (MJ/kg)
Hydrogen	1	Gas	120
Methane	0.25	Gas	50 (43)^2
Ethane	0.2	Gas	47.5
Propane	0.18	Gas (liquid)^1	46.4
Gasoline	0.16	Liquid	44.4
Ethanol	0.13	Liquid	26.8
Methanol	0.12	Liquid	19.9

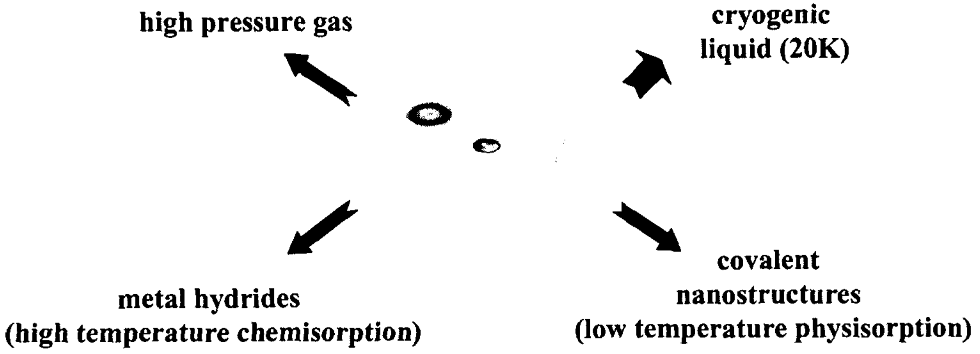
(1) A gas at room temperature, but normally stored as a liquid at moderate pressure.
(2)The larger values are for pure methane. The values in parantheses are for a "typical" Natural Gas.

How large of a gas tank do <u>we</u> want?

Volume Comparisons for 4 kg Vehicular H_2 Storage



Hydrogen Storage Options

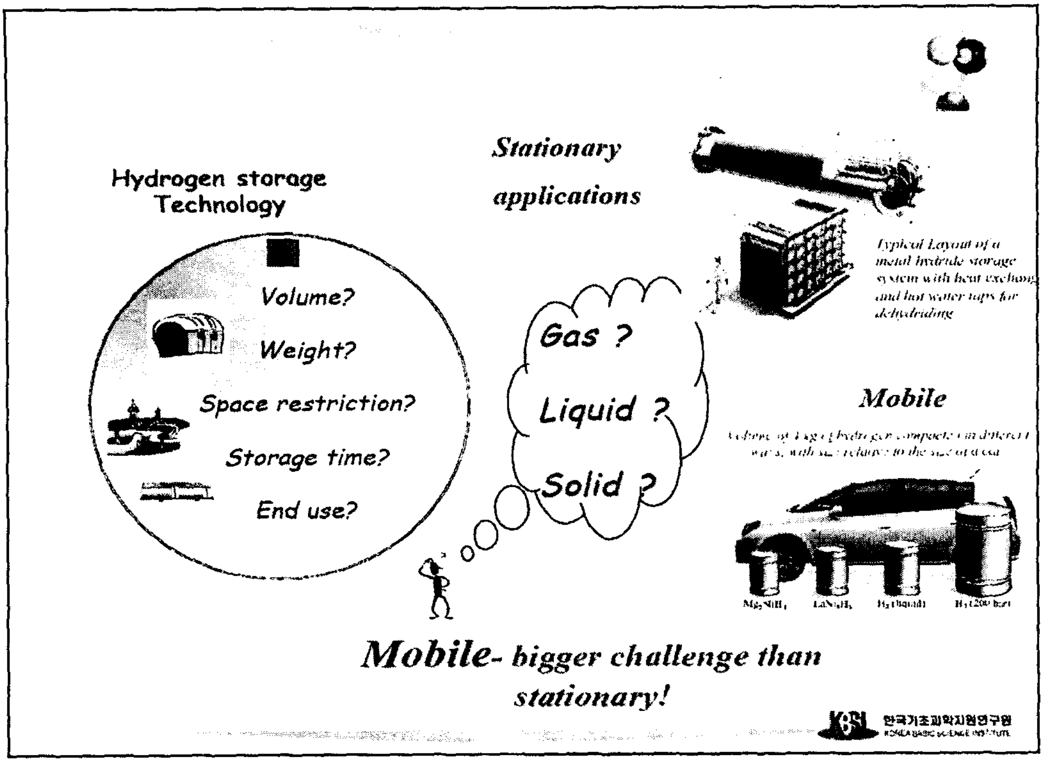


high pressure gas

cryogenic liquid (20K)

metal hydrides (high temperature chemisorption)

covalent nanostructures (low temperature physisorption)



Hydrogen storage Technology

Volume?

Weight?

Space restriction?

Storage time?

End use?

Gas ?

Liquid ?

Solid ?

Stationary applications

Typical Layout of a metal hydride storage system with heat exchang and hot water taps for dehydriding

Mobile

Volume of 4 kg of hydrogen compacted in different ways, with size relative to the size of a car

Mobile- bigger challenge than stationary!

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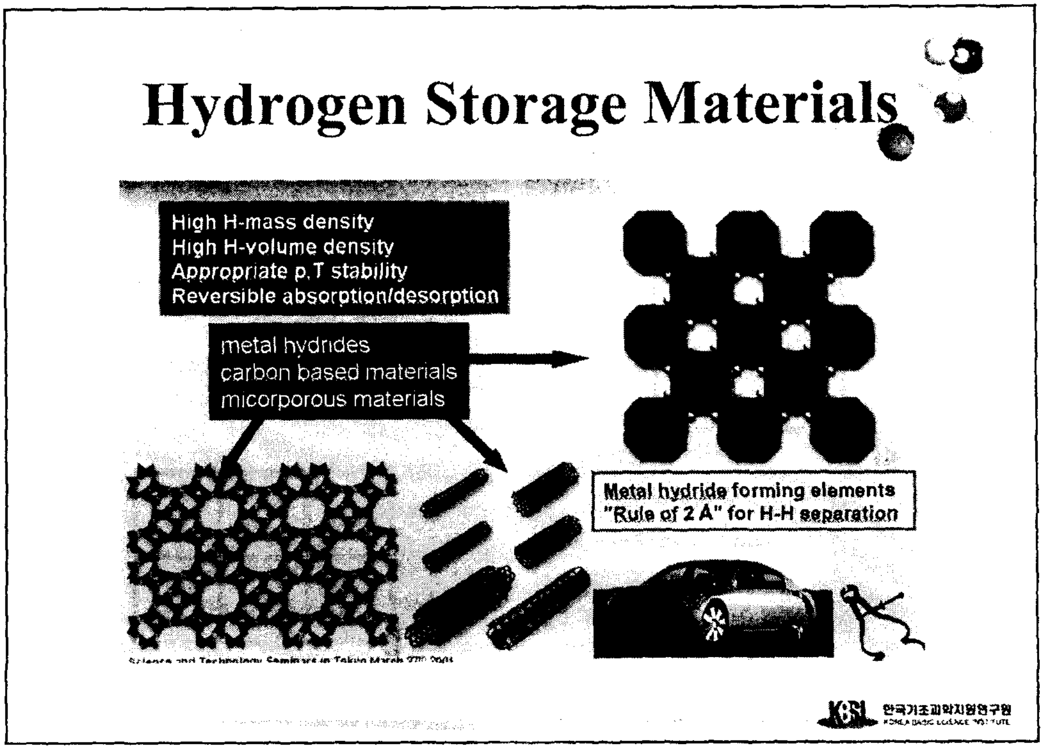

Hydrogen Storage Materials

High H-mass density
High H-volume density
Appropriate p,T stability
Reversible absorption/desorption

metal hydrides
carbon based materials
micorporous materials

Metal hydride forming elements
"Rule of 2 Å" for H-H separation

Science and Technology Seminars in Tokyo March [illegible]

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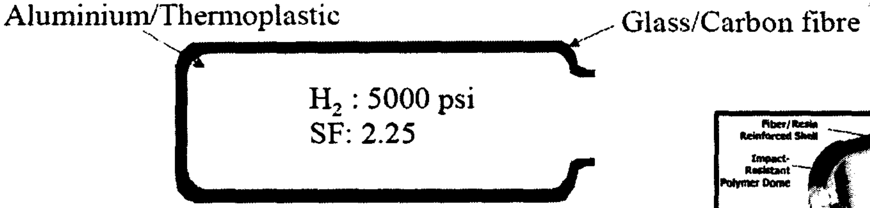
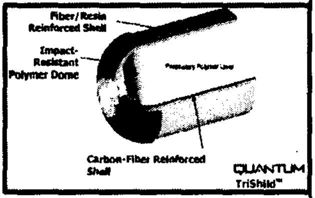
Compressed Hydrogen Storage

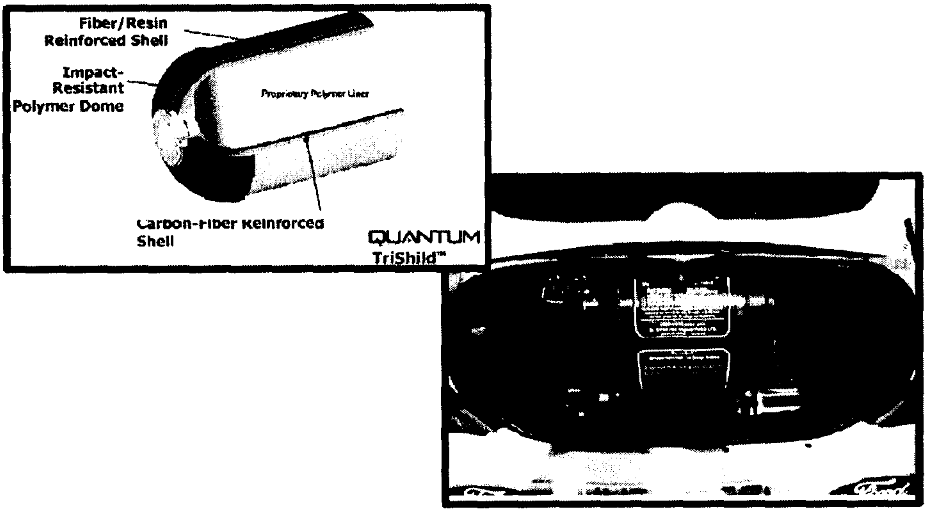




Composite H_2 Cylinder – 12 wt%

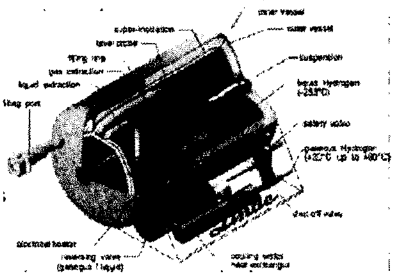
Conformable geometrics
Higher wt% via increased pressure
Heating on filling

Compressed Hydrogen



Liquid Hydrogen Storage

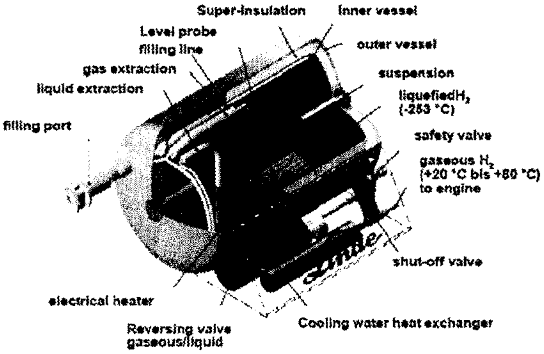
- **Liquid Hydrogen Storage**
- **Cryogenic storage of hydrogen@-253°C**



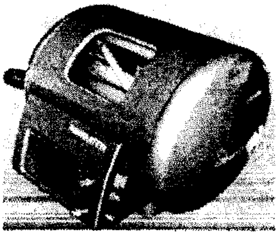
- **Advantages**
  - **√ Low pressure**
  - **√ High storage density**
- **Disadvantages**
  - **√ Energy required for liquefaction**
  - **√ Evaporative losses during fueling**
  - **√ Evaporative losses during periods of inactivity, i.e. when parked**
  - **√ Consumer Acceptance**
- **Future developments to improve packaging and reduce evaporative losses**

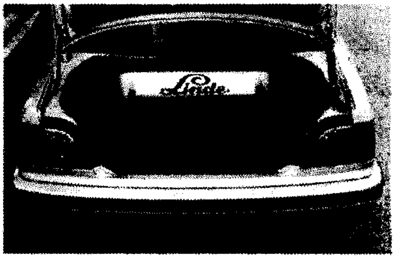
Liquid Hydrogen

Development of Storage Technology



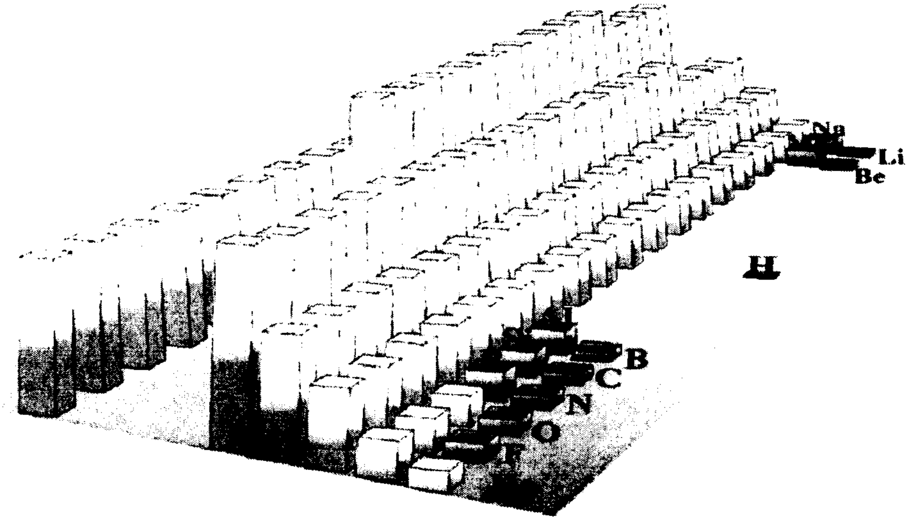
Automotive Design:



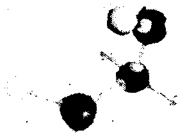


The Periodic Table of the Chemical Elements

The mass of each element is indicated by elevation above the plane



Hydrides



- Binary compounds of hydrogen
  - has an intermediate electronegativity
    - ionic hydrides
      - LiH
    - covalent hydrides
      - HF
    - metallic hydrides
      - NiH_2

Ionic Hydrides

- white solids
- metal cation and hydride ion
- very reactive

$$LiH(s) + H_2O(l) \rightarrow LiOH(aq) + H_2(g)$$

- reducing agents

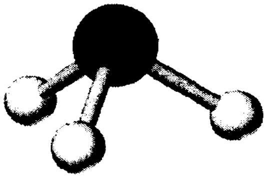
$$CaH_2(s) + H_2O(l) \rightarrow Ca(OH)_2(s) + H_2(g)$$

Covalent Hydrides

- covalently bonds with all nonmetals and weakly electropositive metals
- gases at room temperature
  - hydrogen can be:
    - nearly neutral
    - substantially positive
    - slightly negative

Neutral Covalent Hydrides

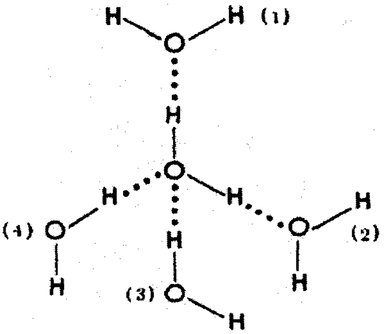
- **low polarity**
  - **only dispersion forces**
- **Examples:**
  - **PH_3**
  - **CH_4**
  - **Hexene**



$CH_4(g) + 2O_2(g) \rightarrow C$ Phosphine

Positive Covalent Hydrides

- **high melting and boiling points**
  - **protonic bridging**
- **Examples:**
  - **ammonia**
  - **water**
  - **hydrogen fluoride**



Negative Covalent Hydrides

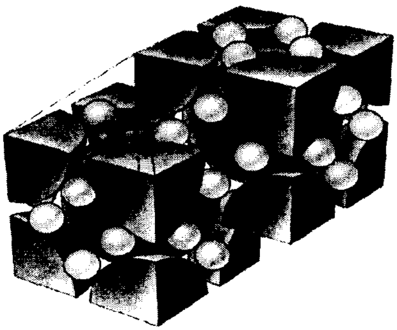
- Contains hydridic hydrogens
- Very reactive towards oxygen
- Examples:
  - B_2H_6
  - SiH_4
  - GeH_4

$$GeH_4(g) + 2O_2(g) \rightarrow GeO_2(s) + 2H_2O(l)$$

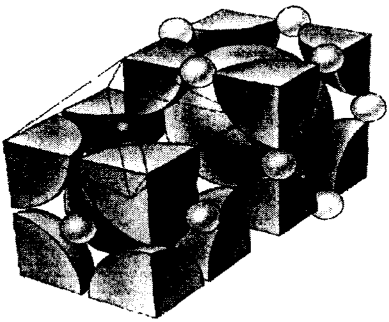
Metalic Hydrides

HYDROGEN INTERCALATION IN METALHYDRIDES

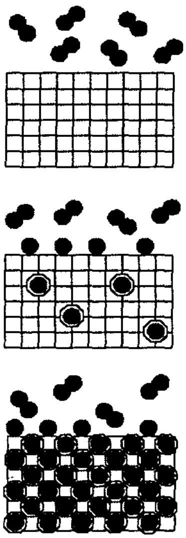
HYDROGEN
ON
TETRAHEDRAL SITES



HYDROGEN
ON
OCTAHEDRAL SITES



HYDROGEN ABSORPTION



Hydrogen gas

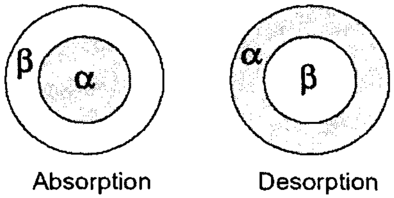
Metal

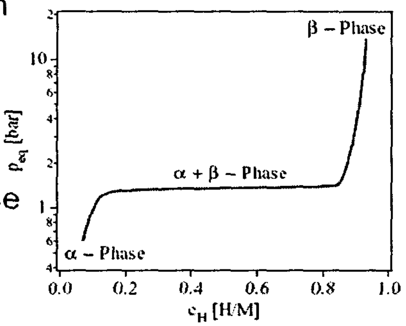
α-Phase: Solid Solution

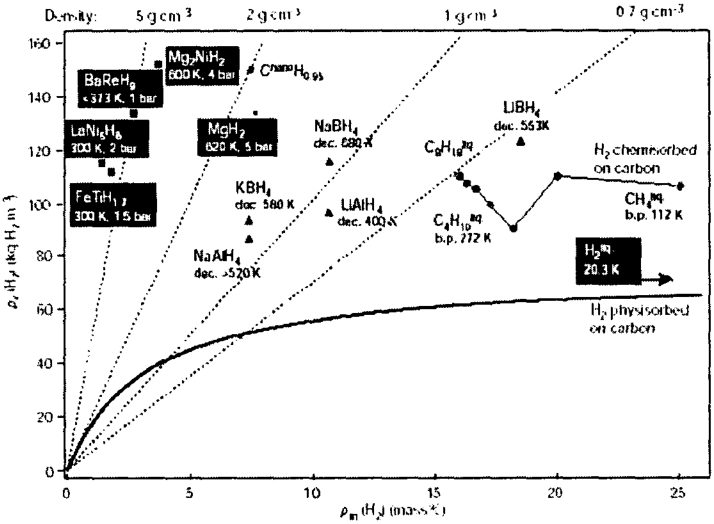
MH_x $(0 < x < 0.1)$
~~$H \leftrightarrow H$~~, $\Delta V/V = k \cdot c_H$

β-Phase: Hydride Phase

MH_x $x = \{1, 2, 3, \ldots\}$
$H \leftrightarrow H$







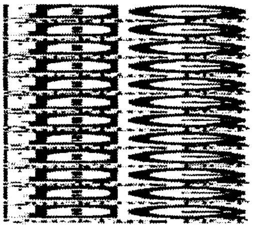
Low mass density = general weakness of all known MH working near RT

Intermetallic compounds & alloys can reach 9 wt.% but are not reversible within the required Ts

Stored hydrogen per mass and volume. Comparison of metal hydrides, carbon nanotubes, petrol and other hydrocarbons.

Hydrogen Storage In MH

- Metal hydride storage



★ safety and long term stability

★ highest capacity by volume

★ high capacity by weight for Mg

★ free geometry

Problem: Storage & Application

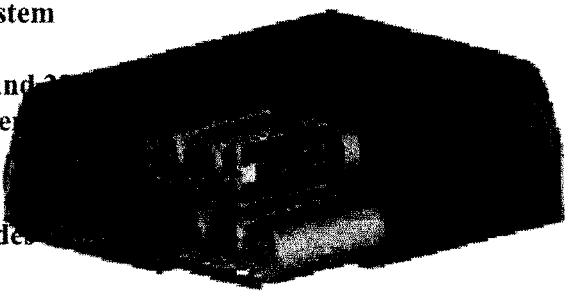
↯ high temperature of operation → 300°C

↯ sluggish → refueling: ≈ several hours

Challenges in development of the storage, transport and distribution infrastructures

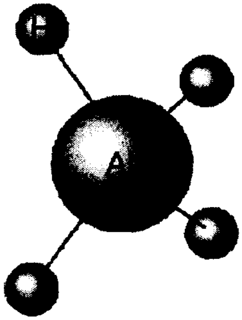
Metal Hydride Storage

- **Current metal hydride system = 1.5 – 5 wt.% H_2**
  - **√ Operate@ 300-400 °C an**
  - **√ Primary challenge is the**
    management
- **Low – temperature hydride**
  development
  - **√ Goal: 5.5 wt %H_2 @ <100 °C**



Complex Hydride

- Complex hydrides consist of a **H=M** complex with additional bonding element(s)
- hydrogen complexes include:
  - **$(AlH_4)^-$** (alanates)
  - **$(BH_4)^-$**
  - with Group VIII elements
- features:
  - ionic, covalent, metallic bonding
  - can have lower formation energy
  - can have high H/M
- 173 complex hydrides listed on *hydpark.ca.sandia.gov*



Irreversible Chemical Hydrides

Three Approaches

$NaBH_4 + 2H_2O \square NaBO_2 + 4H_2$

20 - 35% sol. Stabilized with 1-3% NaOH

Catalyst

Borax in NaOH

$2LiH + 2H_2O \square 2LiOH + 2H_2$

Light mineral oil slurry, proprietary stabilizers

Paste byproduct

- **Hydrogen capacity is high at around 10 wt% hydrogen.**
- **Dehydrogenation kinetics are fast.**
- **Reactions are irreversible on-board vehicle.**

$2Na + 2H_2O \square 2NaOH + H_2$

Polyethylene-coated pellets, mechanically cut to expose Na

Regeneration costs are a major issue

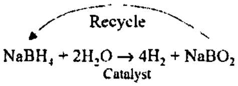
수소연료전지 스쿠터 시운전 성공

수소에너지사업단

국내 기술진이 친환경 미래 에너지의 하나로 각광받는 수소연료전지를 장착한 스쿠터<사진>의 시험 운전에 성공했다.

고효율수소에너지제조저장이용기술개발사업단(단장 김종원)은 18일 한국과학기술연구원(원장 김유승), 삼성엔지니어링(대표 정연주)과 함께 촉매반응을 통해 수소 기체를 발생시키는 방식의 연료전지를 스쿠터에 장착, 1회 연료주입량인 6리터의 화학수소화물(NaBH4) 수용액으로 140㎞ 이상 주행할 수 있었다고 밝혔다.

이번에 개발한 전지는 기존 350기압 저장법보다 1.5~2배 가량 수소 저장밀도를 높일 수 있다.



$$NaBH_4 + 2H_2O \xrightarrow[\text{Catalyst}]{} 4H_2 + NaBO_2$$

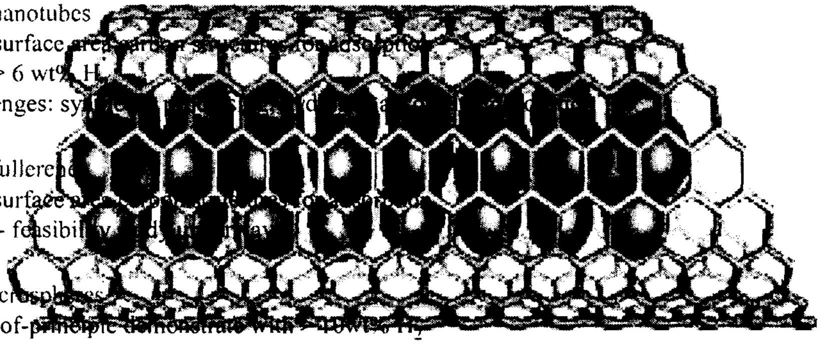
Other complex hydrides: $NaAlH_4$ [7 wt%, 2 stage]
Beryllium hydrides Li_2BeH_4, 8 wt% [Toxicity issues]

Complex Hydrides

- Reversibility
  - role of catalyst or dopant
- Thermodynamics
  - pressure, temperature
- Kinetics
  - long-range transport of heavy species
- Cyclic stability
- Synthesis
- Compatibility/safety

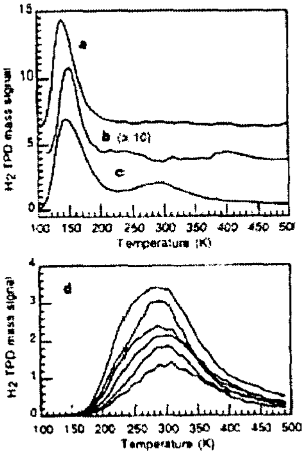
Examples	**Theoretical reversible capacity/ wt%**
$Na(AlH_4)$	**5.6**
$Li(AlH_4)$	**7.9**
$Mg(AlH_4)_2$	**7.0**
$Ti(AlH_4)_4$	**8.1**
$Fe(BH_4)_2$	**9.4**
$Na(BH_4)$	**7.9**
$Ca(BH_4)_2$	**8.6**

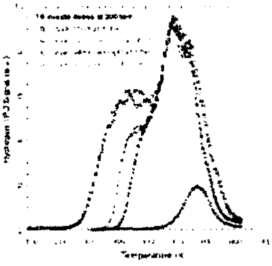
Advanced Solid-State Storage

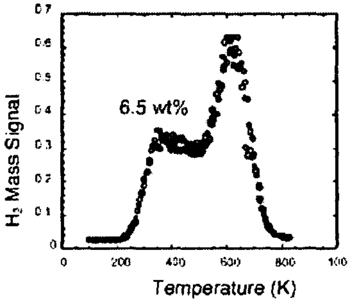


- Carbon nanotubes
  - √ High surface area carbon structure for adsorption
  - √ Goal > 6 wt% H_2
  - √ Challenges: sy [illegible]
- Carbon fullerene
  - √ High surface [illegible]
  - √ Status- feasibility [illegible]
- Glass microspheres
  - √ Proof-of-principle demonstrate with > 10wt% H_2
  - √ Potential for low cost, high-capacity conformable storage
  - √ Challenges: synthesis, processing, thermal/pressure management of adsorption/desorption

Hydrogen in SWCNT

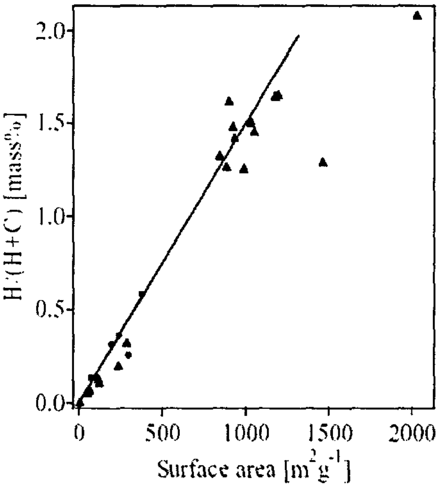






Hydrogen TPD spectrum of a degassed sample, room temperature H_2 exposure at 500 torr. The adsorbed hydrogen corresponds to 6.5 wt%. Hydrogen TPD data from an SWNT sample that was exposed to hydrogen at 300 Torr for 10 minutes followed by a variation in post-dosing conditions.

HYDROGEN STORAGE IN CARBON NANOTUBES



Ref.: M.G. Nijkamp, J.E.M.J. Raaymakers, A.J. van Dillen, K.P. de Jong, Appl. Phys. A 72 (2001), pp. 619–623

Hydrogen gas adsorption at 77 K
electrochemical capacity at 293 K

1.5 mass% / 1000 m^{2}g^{-1}
max. 2 mass%

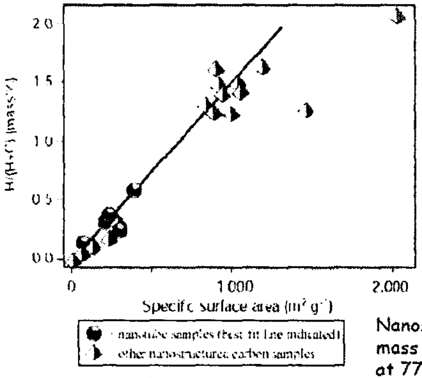
Hydrogen gas adsorption at 296 K and 125 bar:
max. adsorption 1.5 mass%

Ref.: R. Ströbel et al., Journal of Power Sources 84 (1999), pp. 221-224

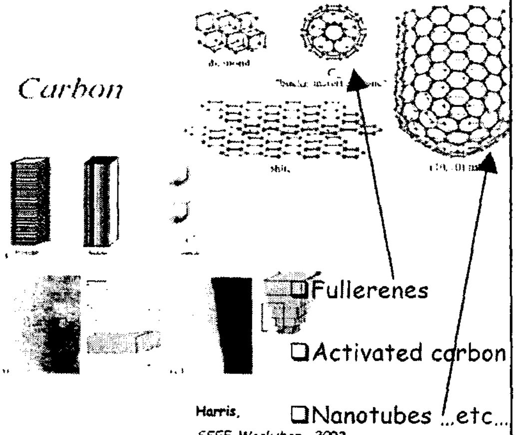
Carbon materials - an alternative to high density storage...

Hydrogen absorbs at solid surfaces depending on the applied pressure & temperature

Reversibly stored amount of hydrogen on various carbon materials vs. the specific surface area of the samples



Schlapbach & Züttel, *Nature* 414, 353-358, 2001

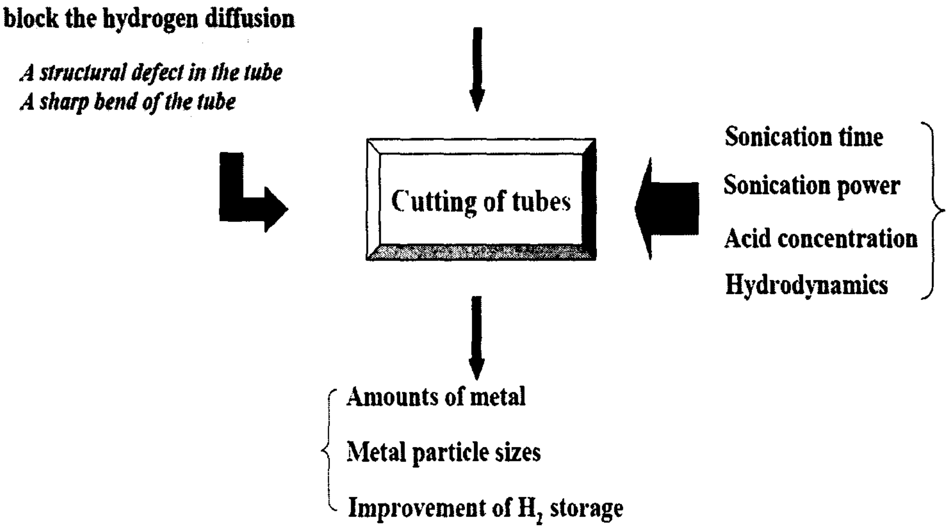


- ☐Fullerenes
- ☐Activated carbon
- ☐Nanotubes ...etc...

Harris,
SEEF Workshop, 2003

Nanostructured graphitic carbon at 77K amounts to 1.5% mass per 1,000m^2/g surface area. Temperature dependent - at 77k one order of magnitude higher than at 300K.

The key point of H_2 storage



block the hydrogen diffusion

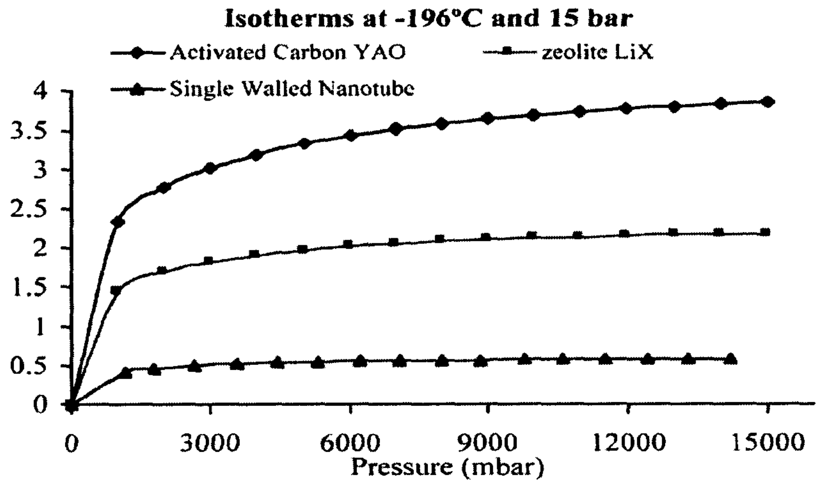
A structural defect in the tube
A sharp bend of the tube

Cutting of tubes

Sonication time
Sonication power
Acid concentration
Hydrodynamics

Amounts of metal
Metal particle sizes
Improvement of H_2 storage

IGA traces (PCT plots) of activated carbon, zeolite and SWNT material at -196°C up to 15 bar with 1 bar pressure steps.



Hydrogen Storage in Carbon

Material	Density wt%	Temp (K)	Pressure (MPa)	Reference	Year
GNFs (herring bone)	67 55	RT	11.35	Chambers	1998
GNFs (platelet)	53.68	RT	11.35	Chambers	1998
Li-MWNTs	20	~473-673	0.1	Chen	1999
K-MWNTs	14	< 313	0.1	Chen	1999
GNFs (tubular)	11.26	RT	11.35	Chambers	1998
CNFs	~10	RT	10 1	Fan	1999
Li/K-GNTs (SWNT)	~10	RT	8-12	Gupta	2000
GNFs	~10	RT	8-12	Gupta	2000
SWNTs (lo purity)	5-10	273	0.04	Dillon	1997
SWNTs (hi purity)	8.25	80	7.18	Ye	1999
CN nanobells	8	573	0.1	Bai	2001
Nano graphite	7.4	RT	1	Orimo	2000
SWNTs (hi p + Ti alloy)	6-7	~300-700	0.07	Dillon	2000
GNFs	6.5	RT	~12	Browning	2000
CNFs	~5	RT	10.1	Cheng	2000
MWNTs	~5	RT	~10	Zhu	2000
SWNTs (hi p + Ti alloy)	3.5-4.5	~300-600	0.07	Dillon	1999
SWNTs (50% purity)	4.2	RT	10.1	Liu	1999
Li-MWNTs	~2.5	~473-673	0.1	Yang	2000
SWNT (50% purity)	~2	RT	echem	Nutzenadel	1999
K-MWNTs	~1.8	< 313	0.1	Yang	2000
(9,9) array	1.8	77	10	Wang	1999
MWNTs	< 1	RT	echem	Beguin	2000
CNF	0.1-0.7	RT	0.1-10.5	Poirier	2001
(9,9) array	0.5	RT	10	Wang	1999
SWNTs	~0.1	300-520	0.1	Hirscher	2000
Various	< 0.1	RT	3.5	Tibbets	2001
SWNT (+ Ti alloy)	0	RT	0.08	Hirscher	2001

>10 wt%

< 1 wt%

Comparison of H_2 storage

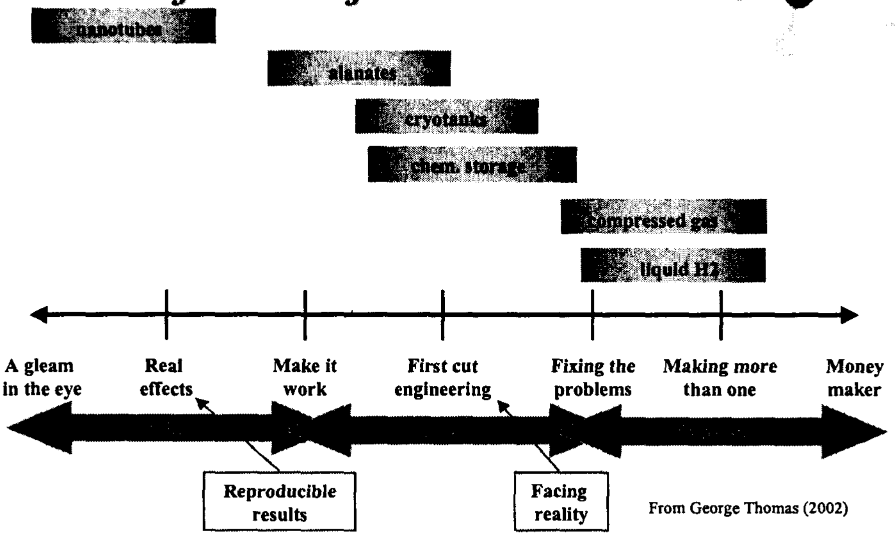
Different types								
	Process	Energy involved in the process	Storage pressure	Temperature (°C)	Volumic density	mass ratio (%)	specific energy	Energy needed for H_2 release
compressed	Mutiple steps adiabatic compression – cooling	3.3 kWh kg H_2	200-350 to 800 bar	25 °C	max. 33 kg H_2 m^3	1.1 à 2.6 (200 bar) 11.5-13 (700-800 bar)	0.45 à 5 kWh kg	0
Underground storage	Aquifers Salt caverns		80 – 160 bar					
liquefied	Liquid N_2 cooling – Mutiple steps adiabatic compression	10 kWh kg H_2	No data	- 253 °C	71 kg H_2 m^3	26	14 kWh kg	0 1 to 3 % loss per day
$NaBH_4$ *Hydrogen on demand*™	$NaBH_4$ – 2 H_2O + catalyst ⇒ $NaBO_2$ + 4 H_2	No data	No data	No data	No data	No data	No data	0
Metal hydrides	chimisorption desorption	No data	2 to 10 bar	0-100 °C	max. 150 kg H_2 m^3	2	0.8 à 2.3 kWh kg	No data
Active carbons	physisorption desorption	No data	250 bar	25 °C	18 kg H_2 m^3	No data	2.2 kWh kg	No data
Carbon nanofibres & nanotubes	physisorption desorption	No data	125 bar	25 °C	No data	1.5	1.7 à 3 kWh kg	No data
fullerens	chimisorption desorption	100kJ mol (14 kWh kg of H_2 ?)	27 bar	100-200 °C	No data	6 – 7.7	2.5 kWh kg	160kJ mol (22 kWh kg H_2 ?)

Maximum storage densities

Energy Density MJ/liter

- High pressure gas
  - ambient temperature — 3600 psi: 2.0 — 5000 psi: 2.75
  - cryogenic system — 150 K: 3.5 — 20 K: 8.4
- Liquid hydrogen — 8.4
- Reversible storage media
  - carbon structures
    - nanotubes — ?
    - fullerenes — ?
  - hydrides
    - intermetallics — 10.8 - 12.0
    - alanates — 8.25
  - composite materials — ?
- Chemical methods — Eff. — gasoline — methanol
  - liquid fuel + reformer — 50%: — 6.6 — 5.9
  - 75%: — 9.9 — 8.9
  - *off-board reprocessing* — ?

The most promising technologies are the farthest from commercialization

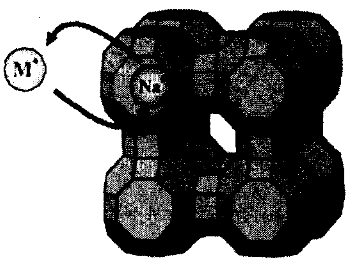


From George Thomas (2002)

Advanced storage approaches identified

1. Crystalline Nanoporous Materials
2. Polymer Microspheres
   Self-Assembled Nanocomposites
3. Advanced Hydrides
4. Metals – Organic
5. BN Nanotubes
   Hydrogenated Amorphous Carbon
6. Mesoporous materials
7. Bulk Amorphous Materials (BAMs)
8. Iron Hydrolysis
9. Nanosize powders
10. Metallic Hydrogen
    Hydride Alcoholysis

Hydrogen Uptake in Zeolite



Zeolite A

- Low cost, chem.&therm. Robust
- Good structural reproducibility
- Environmentally friendly &safe

	H_2 uptake (wt.%)		
Material	-196°C	RT	270°C
NaA	1.54	0.28	0.30
CdA	1.14	0.25	0.30
MgA	1.19	-	-
NaCsRHO	0.00	0.18	0.20
CdRHO	0.08	0.19	0.25
LiX	2.15	-	-
NaX	1.79	-	0.25
CdX	1.42	-	-
MgX	1.61	-	0.28
CuX	-	-	0.25
NaY	1.81	-	-
CdY	1.47	-	-
MgY	1.74	-	-

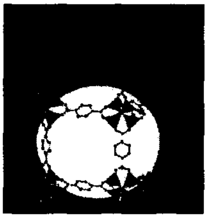
15bar H_2

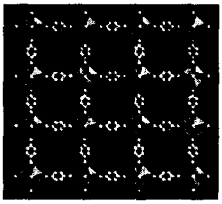
Mesoporous Metal Organic (MOF-5)

Single-crystal x-ray structures of MOF-5(A), IRMOF-6(B), and IRMOF-8(C)
Zn (blue polyhedra), O (red spheres), C (black spheres)

4.5 wt% at 78 K (A)
1.0 wt% at RT and 20 bar (B)

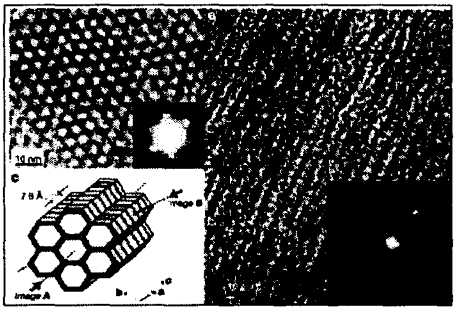
Hydrogen gas sorption isotherm for MOF-5 at (A) 78 K and (B) 298 K





- Chemical formula Zn$_4$O (BDC)$_3$ (DMF)$_8$ (C$_6$H$_5$Cl)
  - *BCD = 1,4 - benzenedicarboxylate*
  - DMF = dimethylformamide
- ZnO$_4$ tetrahedral clusters linked together by C$_6$H$_4$-C-O$_2$ "struts"
- *Cubic crystal structure*
- 1.294 nm spacing between centers of adjacent clusters
- **What are the hydrogen storage characteristics of this material?**

Mesoprous Organosilica Material



benzene-silica hybrid material

Hydrogen storage behavior?

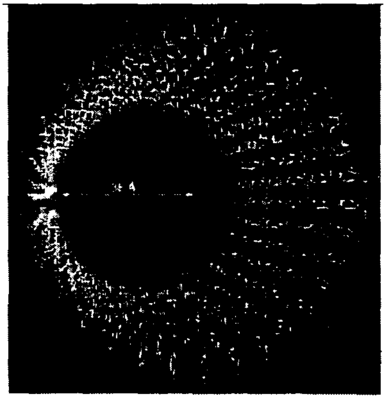


Figure 4 Model showing the pore surface of mesoporous benzene–silica. Benzene rings are aligned in a circle around the pore, fixed at both sides by silicate chains. The silicate is terminated by silanol (Si–OH) at the surface. Hydrophobic benzene layers and hydrophilic silicate layers array alternately at an interval of 7.6 Å along the channel direction. Silicon, orange; oxygen, red; carbon, white; hydrogen, yellow

Boron Nitride Nanotube

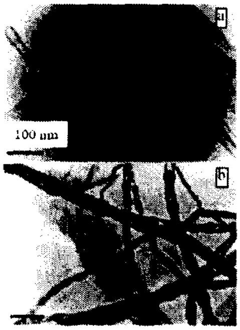


Figure 1. The morphologies of BN nanotubes: (a) multiwall nanotubes and (b) bamboo-like nanotubes. Scale bar = 100 nm

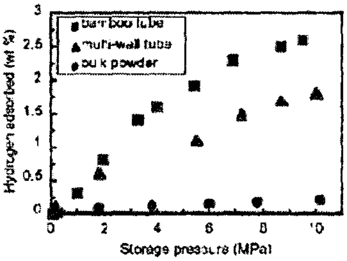
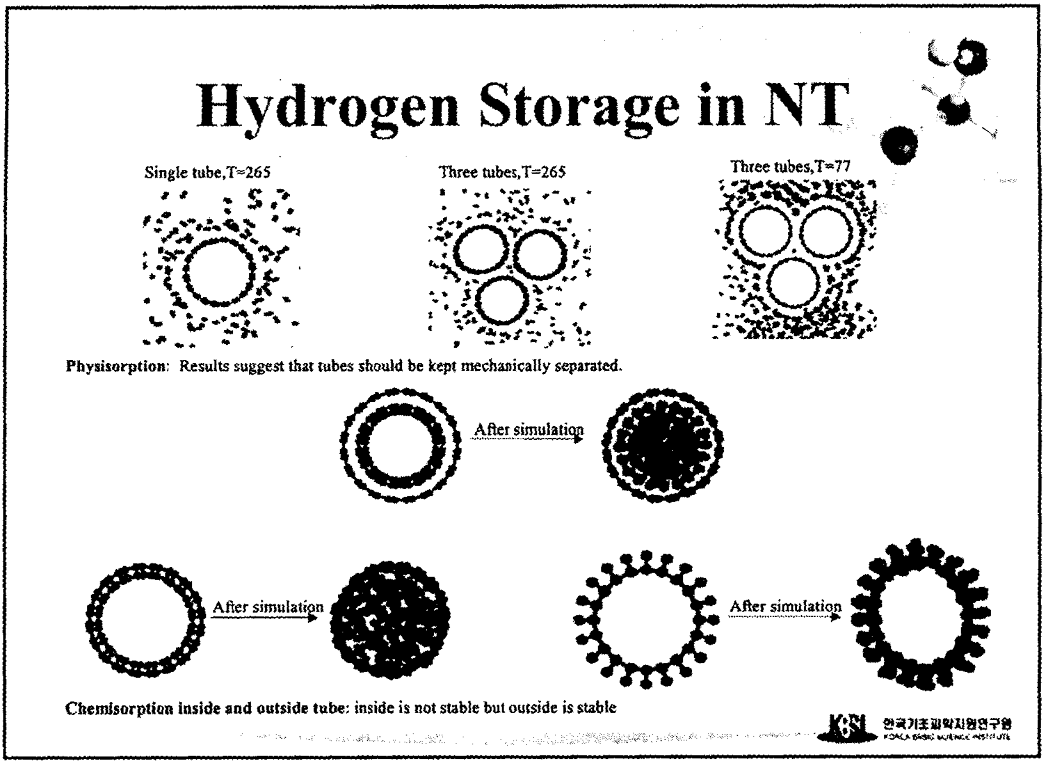


Figure 2. The hydrogen absorption as a function of pressure in multiwall BN nanotubes and bamboo nanotubes at ~10 MPa is 1.8 and 2.6 wt %, respectively, in sharp contrast to the 0.2 wt % in bulk BN powder. The values reported here have an error of ±0.3 wt %.

Multiwall : 1.8 wt%
Bamboo-like : 2.6 wt%

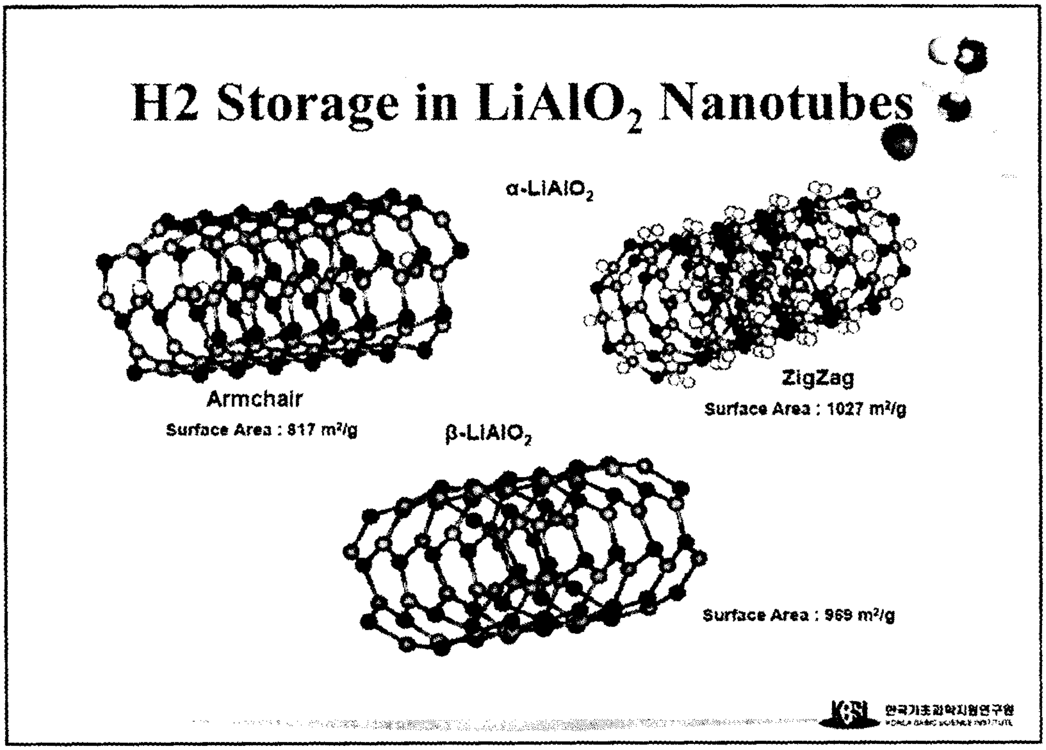
Hydrogen Storage in Inorganic Nanostructured Materials at KBSI



Hydrogen Storage in NT

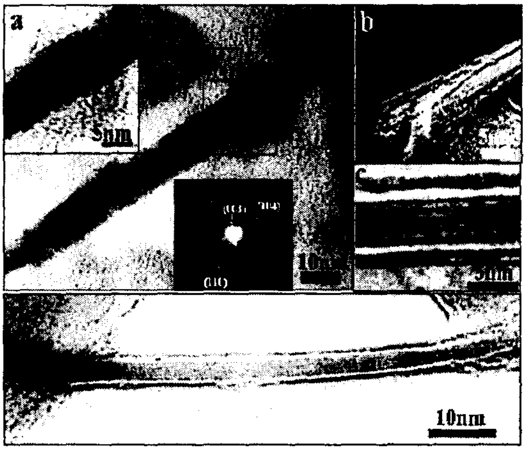
Physisorption: Results suggest that tubes should be kept mechanically separated.

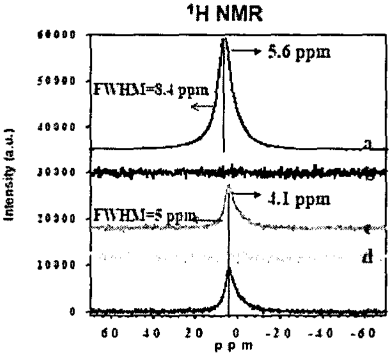
Chemisorption inside and outside tube: inside is not stable but outside is stable



H2 Storage in $LiAlO_2$ Nanotubes

H_2 storage in $LiAlO_2$ Nanotube





(a) P-ANT-Li before evacuation

(b) Evacuation at RT 54h

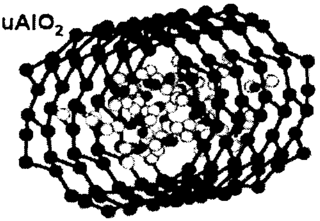
(c) H_2 adsorption at RT, 2.7atm 45h

(d) Re-evacuation at RT 10min

(e) H_2 re-adsorption at RT, 2.7atm 45h

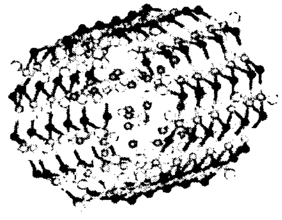
H_2 uptake in M-oxide Nanotubes

$CuAlO_2$



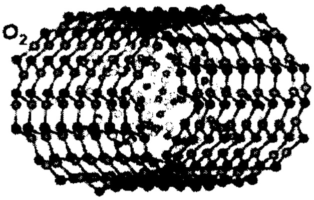
Surface Area : 1128 m²/g

$LiTi_2O_4$



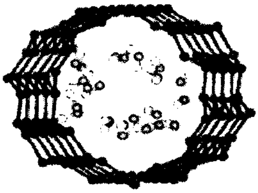
Surface Area : 1860 m²/g

$LiMnO_2$



Surface Area : 2949 m²/g

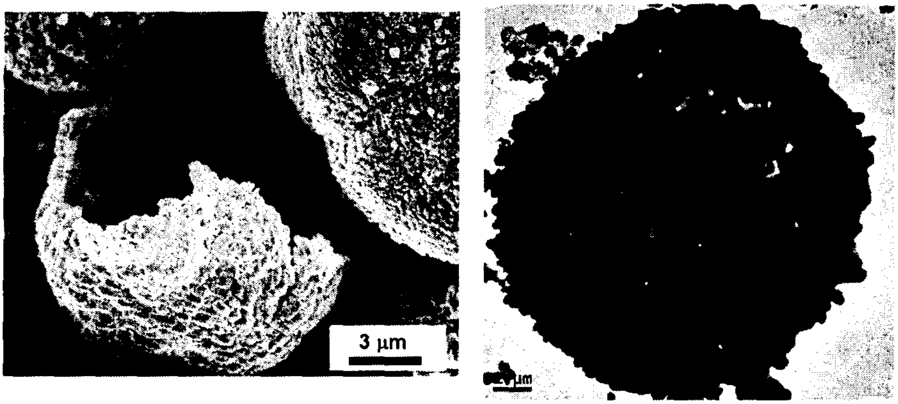
$LiNiO_2$



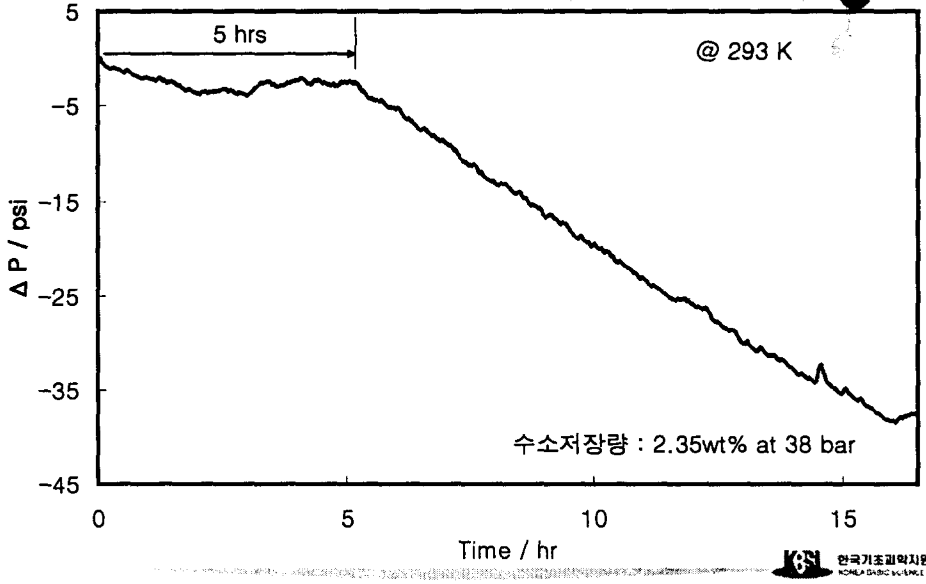
Surface Area : 1322 m²/g

$Cu_2Cl(OH)_3$ microspheres

Biomimetic control을 통한 $Cu_2Cl(OH)_3$ aggregate microsphere

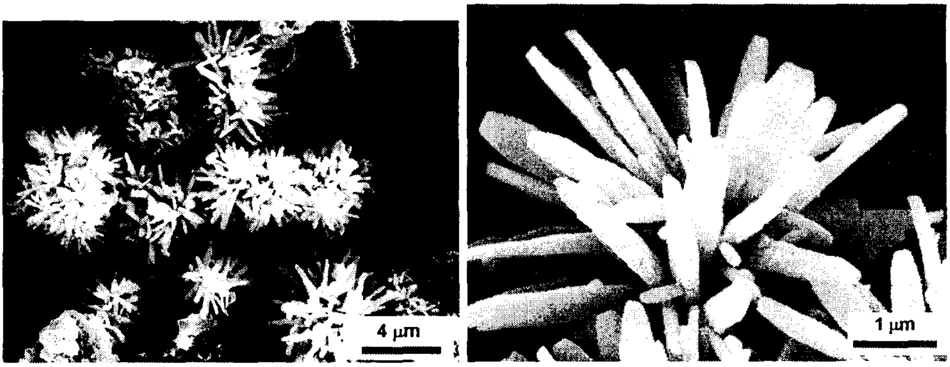


H2 Storage in calcinated $Cu_2Cl(OH)_3$ microspheres



$CuAlO_2$ nanoflower

계면활성제의 상평형도를 이용한 morphology 제어와 이것을 Template로 고상법을 이용하여 $CuAlO_2$ 나노구조체 합성



H_2 Storage : 0.66 wt% @RT, 45 bar

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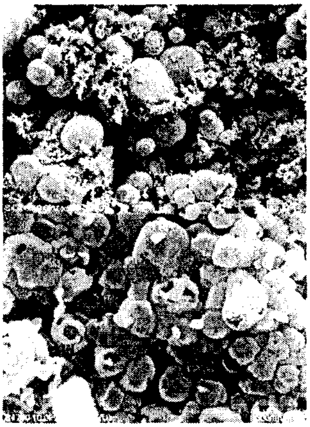
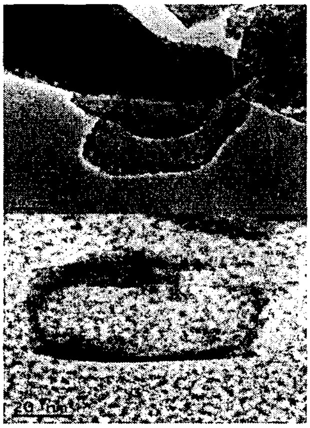
Candidate for H2 Uptake Materials

$LiMnO_2$ Nanomaterials



SEM Images



TEM Images

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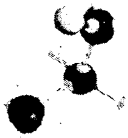
Summary



- Hydrogen storage, even though still at its infancy, appears as a possible attractive alternative.
- Improved safety and energy density

A breakthrough in Hydrogen storage technology could facilitate the introduction of H economy society.